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# Understanding Raman Scattering in NIF Ignition Experiments

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P. A. Michel, L. Divol, R. L. Berger, J. D. Moody

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# **Understanding Raman Scattering in NIF Ignition Experiments**

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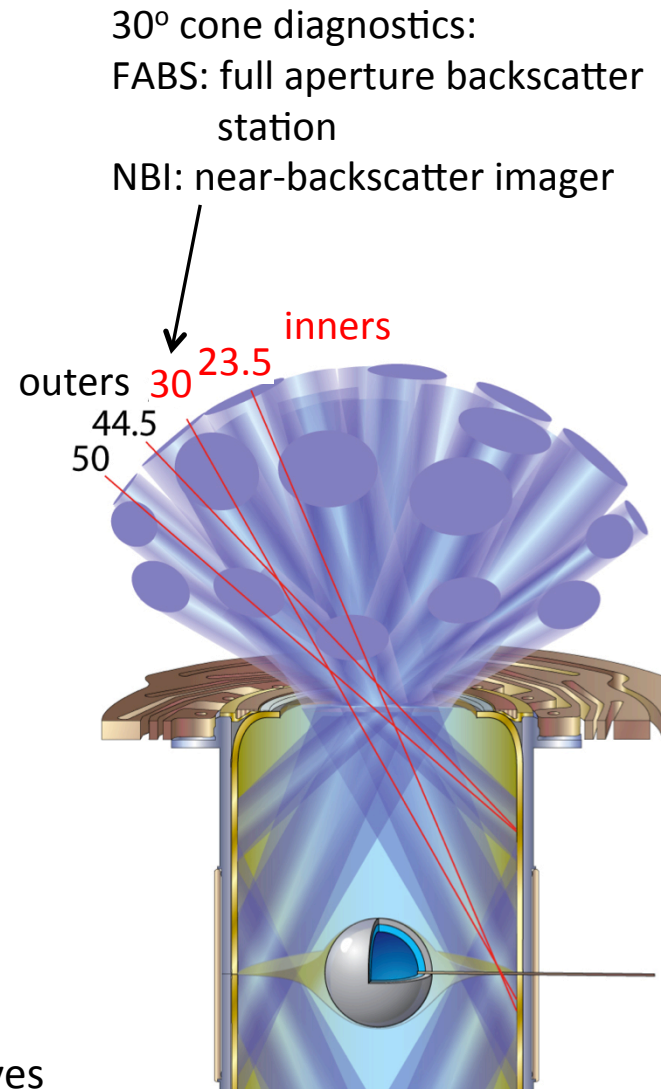
Anomalous Absorption Conference  
20 June 1011

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# Linear gain analyses better match reflectivity trends with improved plasma and laser beam models

- **“High Flux Model” (HFM)** for rad-hydro:
  - DCA opacities, 0.15 electron heat flux limiter
  - Cross-beam energy transfer (linear model with clamp)
  - Measured backscatter removed
- **Linear gain spectrum** with HFM plasma conditions:
  - Close to measured SRS wavelength
  - Agreement better if multi-quad (overlapped beam) laser intensity used, rather than single-quad
- **Gain and reflectivity time histories:**
  - Gain increases in time, while reflectivity first increases and then decreases late in peak power
- **Spatially non-uniform cross-beam energy transfer:**
  - Gain decreases late in peak power, like measured reflectivity
- **Electron trapping:** pF3D simulations give SRS Langmuir waves above threshold for trapping nonlinearities

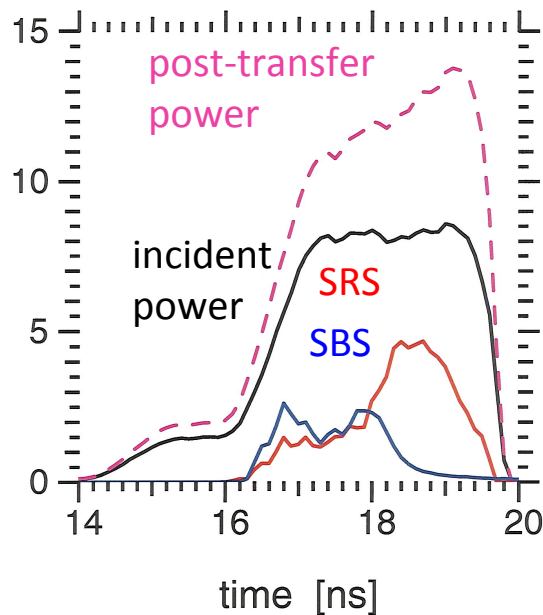




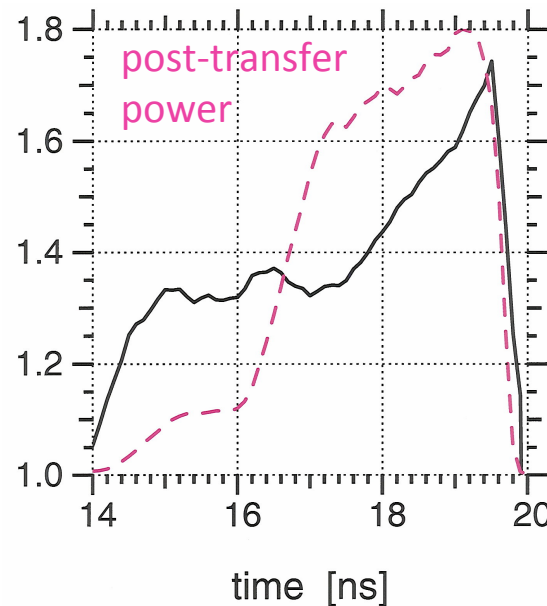
# We study NIF shot N110214 - symmetry capsule (symcap) with ~1.3 MJ laser energy - 30° (inner) cone

- “Post-transfer” reflectivity = measured SRS / Lasnex power w/ cross-beam transfer.
- SRS energy reflectivity [joules out / joules in]:
  - Incident power: 27%
  - Post-transfer power: 19%

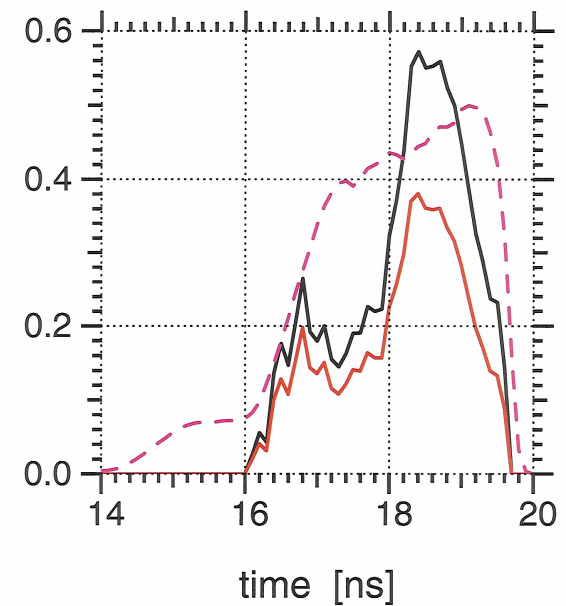
Power on one quad [TW]



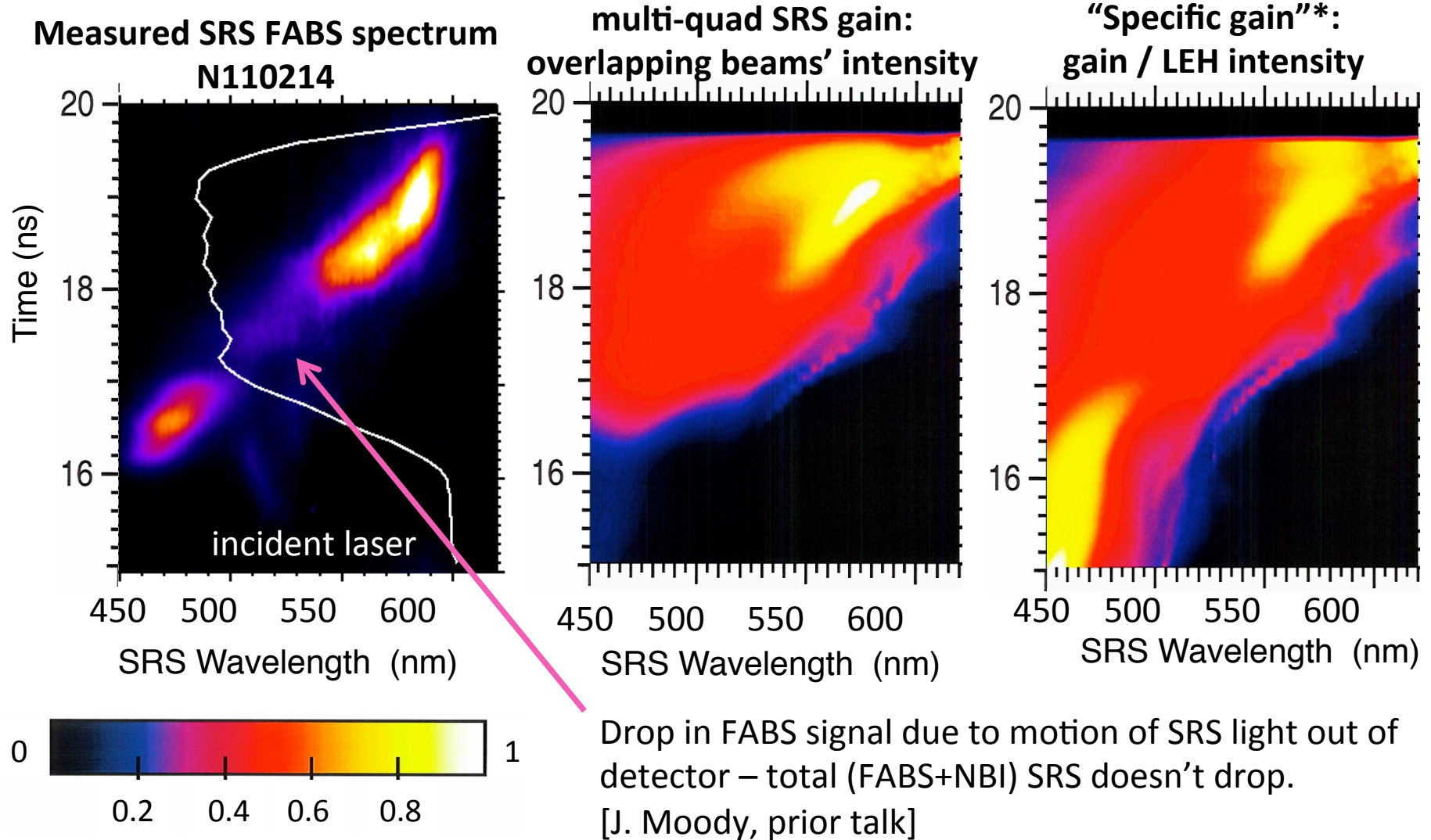
post-transfer power  
incident power



SRS reflectivity:  
nominal, **post-transfer**



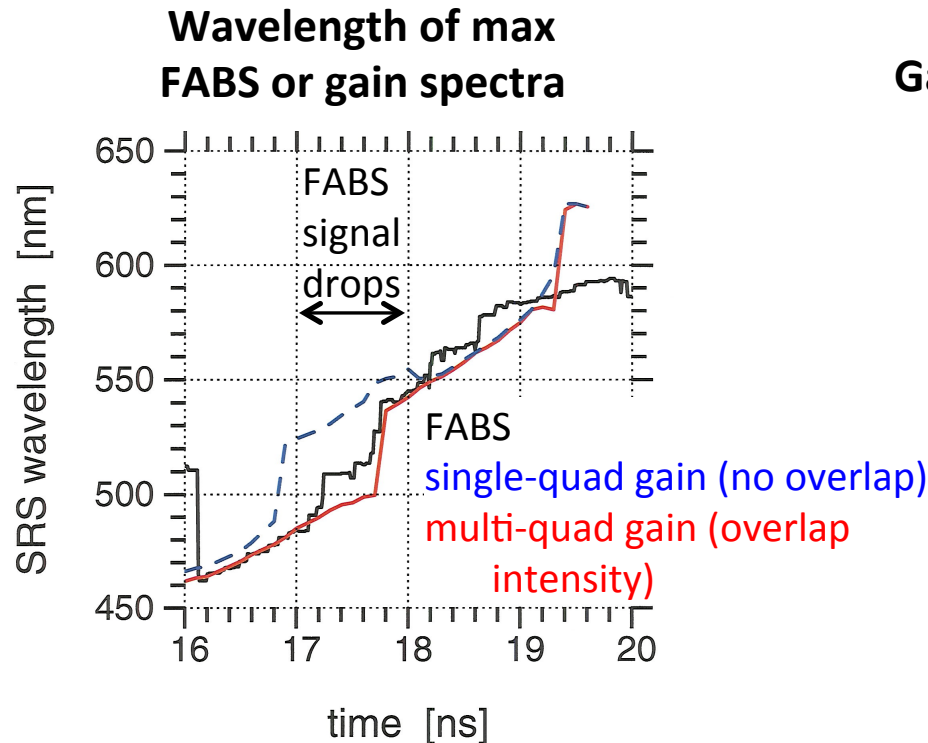
# SRS wavelength increases in time, indicating SRS occurs at progressively higher density



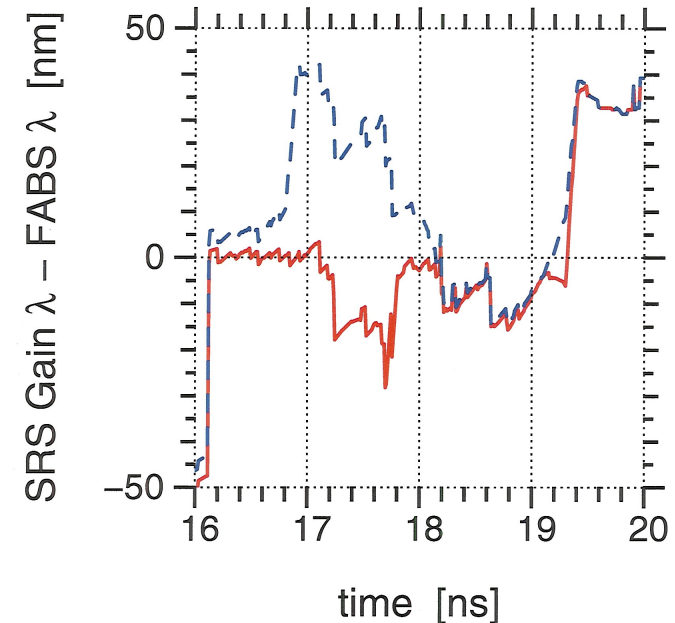
FABS = full aperture backscatter station  
NBI = near-backscatter imager

\*Suggested by L. Suter

**With HFM (high-flux model), wavelength of peak multi-quad gain agrees well with FABS, indicating plasma conditions are ~ right**

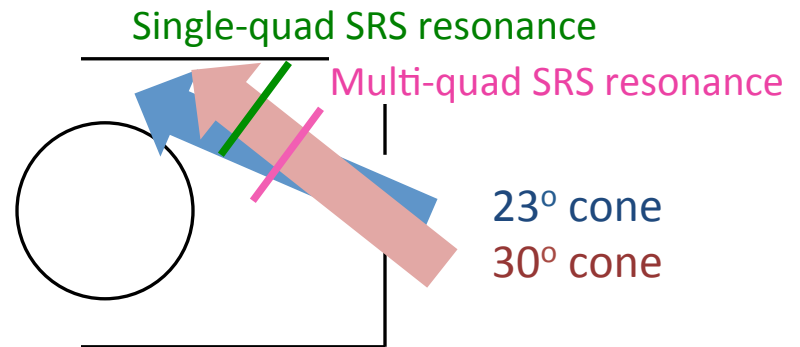
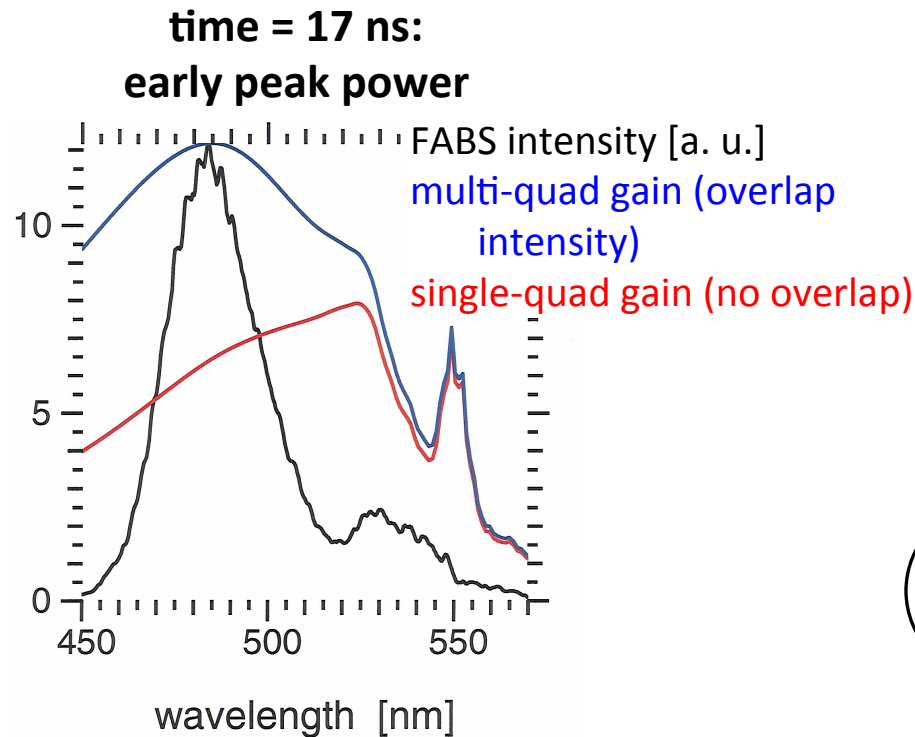


**Gain wavelength – FABS wavelength**



- Wavelength of max SRS separates power history from plasma conditions.
- Early peak power: 17-18ns:
  - Single-quad gains peak at a longer wavelength.
  - FABS signal reduced due to motion of SRS.
  - longer wavelengths refract more, so FABS light may be shorter wavelength than total SRS light.

# Multi-quad SRS gains peak at shorter wavelength since beams overlap near laser entrance hole

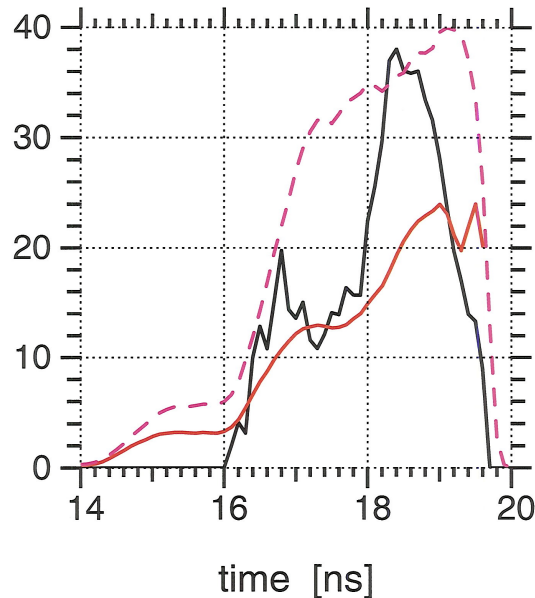


Multi-quad SRS gains peak at shorter wavelength than single-quad gains:  
beams overlap more near the LEH, where the electron density, and plasma frequency, is lower.

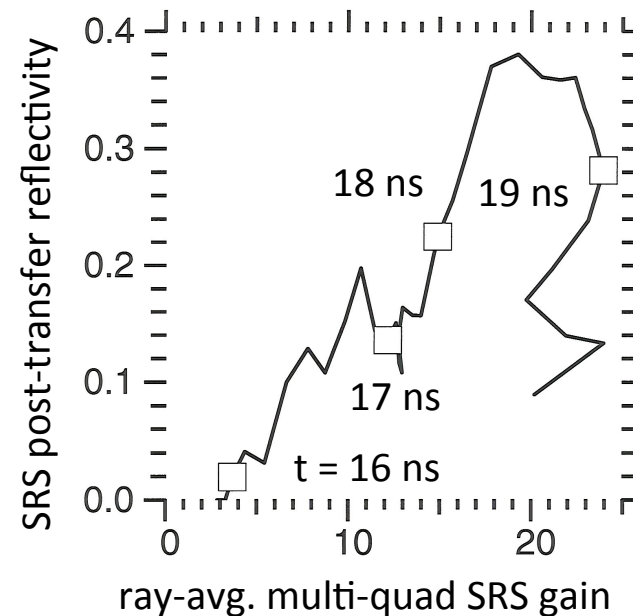
# Spatially uniform transfer: reflectivity scales with gain until late in peak power

post-transfer reflectivity [%]

ray-avg. multi-quad gain



“fruit plot:”  
reflectivity vs. gain

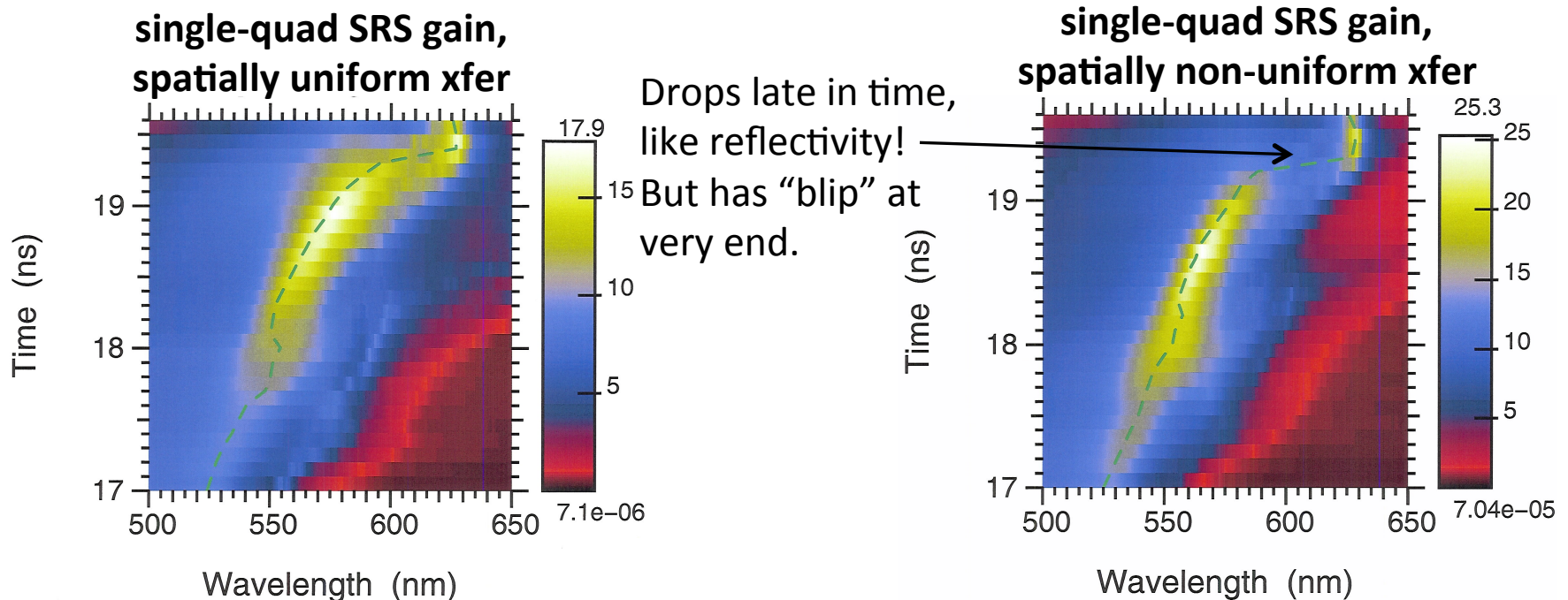


----- post-transfer power

- Gain tracks reflectivity until  $\sim 18.5$  ns (mid-late peak power).
- At late time, reflectivity drops but gain doesn't.
- Late-time gain coming from long wavelengths - generally not observed in FABS.

# More detailed calculations of cross-beam transfer introduce spatial non-uniformity in the intensities

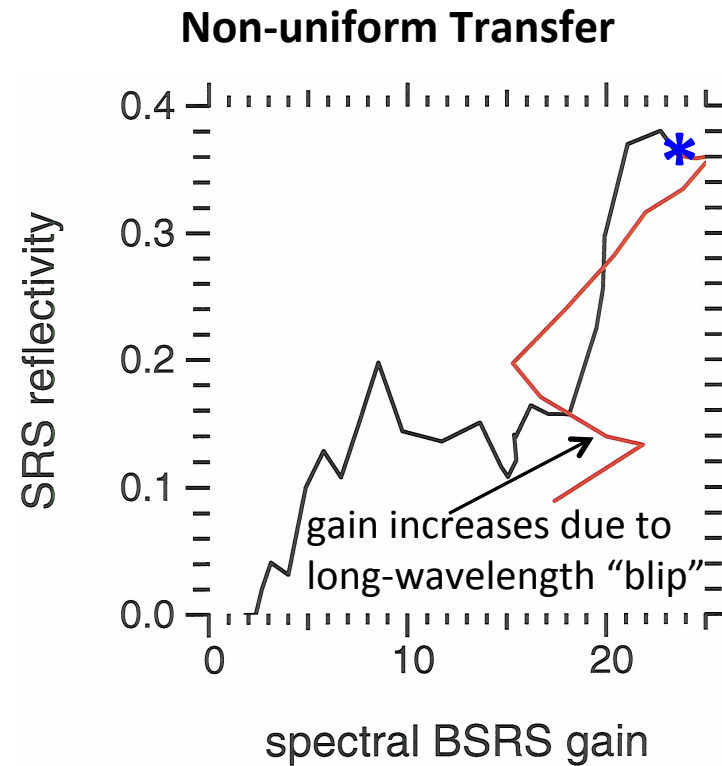
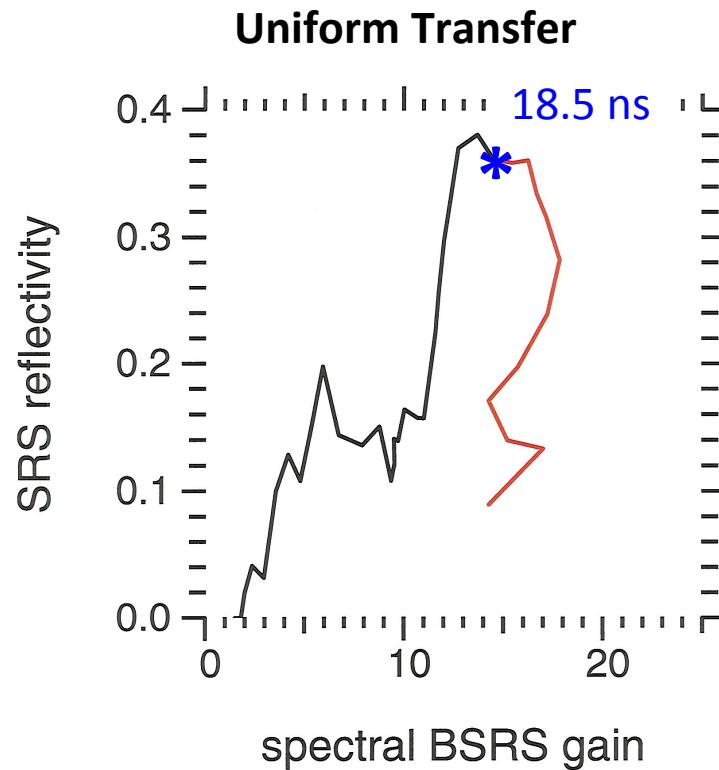
- Current HFM: distributes transferred power uniformly across the beam
- Account for spatial non-uniformity: run SLIP at one time (18 ns): E. A. Williams, later talk
- Provides 3D spatial beam intensity multiplier. Use this mask at all times
- Calculate SRS gain with spatially non-uniform transfer, and single intensities



The spatial non-uniformity of cross-beam transfer improves the correlation between SRS and gain



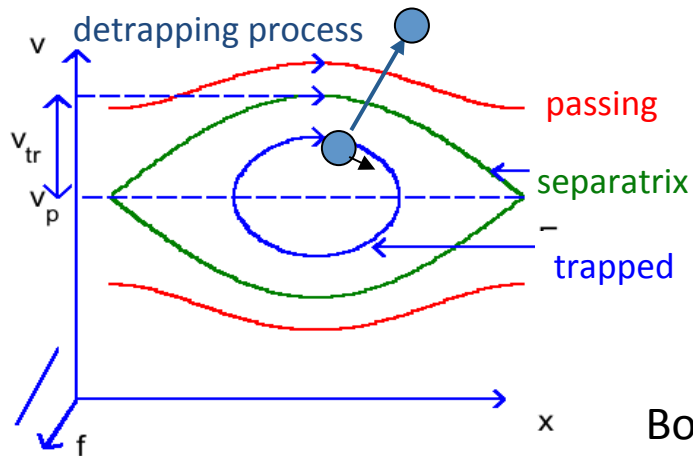
# SRS gain with spatially non-uniform beam transfer tracks reflectivity better than with uniform transfer



# Threshold for electron trapping nonlinearity given by “bounce number” $N_B$

## • Electron trapping nonlinearities:

- Landau damping reduction, frequency shift, Langmuir-wave self-focusing.
- Effective only if electrons resonant w/ Langmuir wave complete  $\sim 1$  bounce orbit before being detrapped.



## Important detrapping processes:

1. Speckle sideloss (geometric effect):  $N_{B,sl}$
2. Collisions: electron-electron and electron-ion treated together:  $N_{B,coll}$   
(SSD way too slow to matter)

Bounce number: 
$$N_B \equiv \frac{\tau_{de}}{\tau_B} = \frac{\text{detrapping time}}{\text{bounce period}} \sim \delta n^{1/2}$$

sideloss: 
$$N_{B,sl} = \left[ \frac{\delta n}{\delta n_{sl}} \right]^{1/2} \quad \delta n_{sl} = 2.67 \left( \frac{8}{F} \frac{\lambda_{De}}{\lambda_0} \right)^2$$

Bounce period: 
$$\tau_B \equiv \frac{2\pi}{\omega_{pe}} \sqrt{\frac{n_e}{\delta n}}$$

collisions: 
$$N_{B,coll} = \left[ \frac{\delta n}{\delta n_{coll}} \right]^{3/2}$$

Joint bounce number: 
$$N_B^{-1} = N_{B,sl}^{-1} + N_{B,coll}^{-1} \quad \text{Independent detrapping rates add.}$$



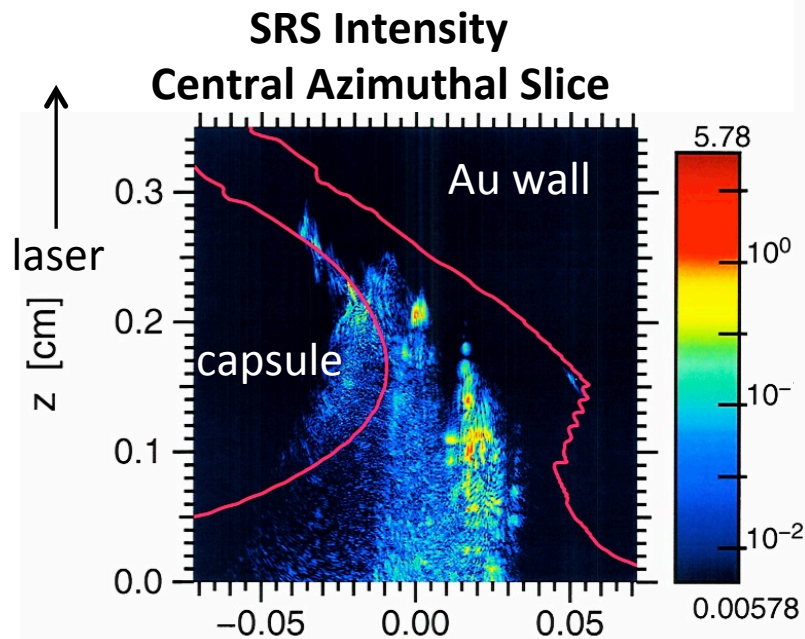
# Trapping assessment of pF3D run suggests trapping occurs in parts of the 30 degree beam

pF3D:

- parallel, paraxial envelope code
- linear plasma response used

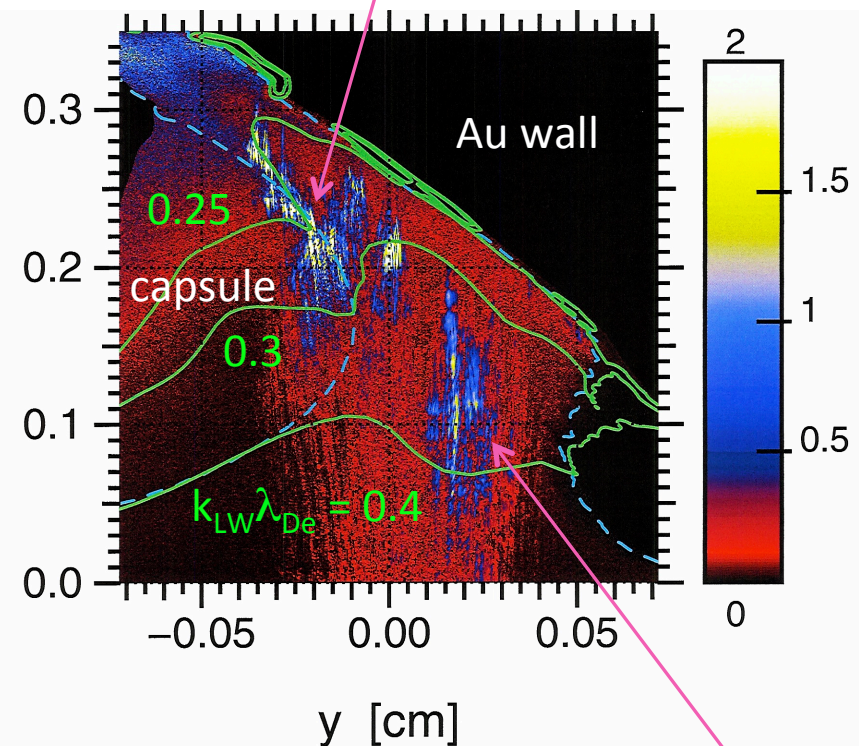
N110214 profiles, time = 18 ns:

- Trapping can change the local gain
- pF3D SRS reflectivity  $\sim 20\%$



Risk of trapping or Langmuir Decay Instability

**bounce number  $N_B \sim [\delta n_{LW}]^{1/2}$**   
**(sideloss and collisions)**



Risk of trapping

# Conclusions

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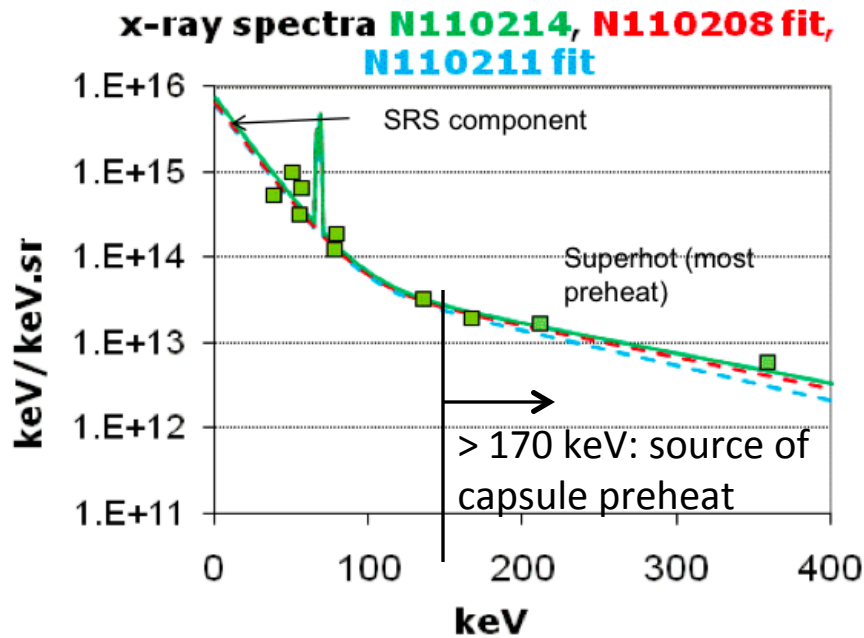
- “High Flux Model” rad-hydro with spatially uniform cross-beam energy transfer:
  - SRS gain spectrum agrees well with measurements
  - Especially when multi-quad laser intensity used
  - Except for long-wavelength gains late in time – not seen in experiments
- Spatially uniform transfer: reflectivity and gain correlate until late in peak power
  - Late in time, reflectivity drops but gain does not
- Spatially non-uniform transfer: the correlation of reflectivity and gain improves
- Electron trapping: pF3D simulation shows regions in the beam where Langmuir wave amplitudes above threshold
  - May play a role in some of the SRS seen

A cross-beam transfer model, including spatial non-uniformity and plasma profile modification, is being added to Hydra

# Backup slides after here

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# Observed SRS is consistent with the colder component of the hot electron spectrum



$$\frac{dN}{dE} \sim \frac{E_1}{T_1^2} \exp[-E / T_1] + \frac{E_2}{T_2^2} \exp[-E / T_2]$$

“SRS component”:

$$E_1 = 70 \text{ kJ}, \quad T_1 = 18 \text{ keV}$$

$$0.5 m_e v_{\text{ph,LW}}^2 = 18 \text{ keV for } \lambda_{\text{SRS}} = 570 \text{ nm}$$

“conventional” backward SRS, measured in FABS/NBI

“Superhot component”:

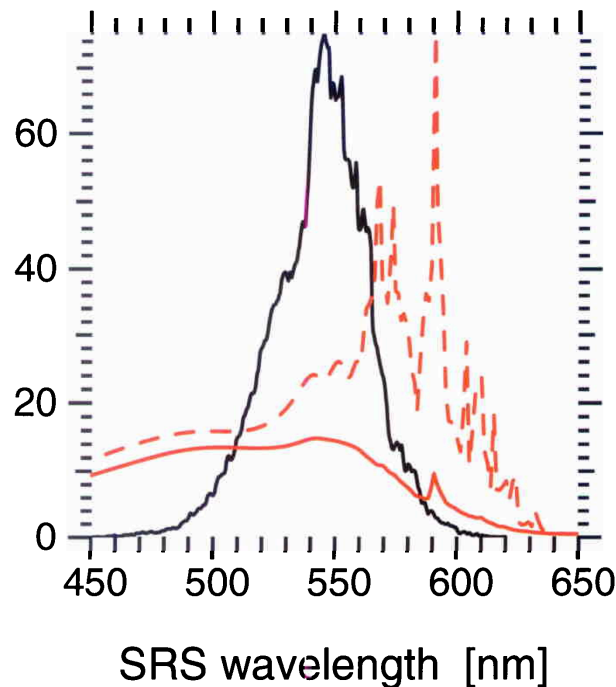
$$E_1 = 0.8 \text{ kJ}, \quad T_1 = 124 \text{ keV}$$

independent LPI process, such as:

two-plasmon decay, backward SRS at  $n_{\text{crit}}/4$ , forward SRS, ...

# Significant gain can occur at longer wavelengths than measured on FABS

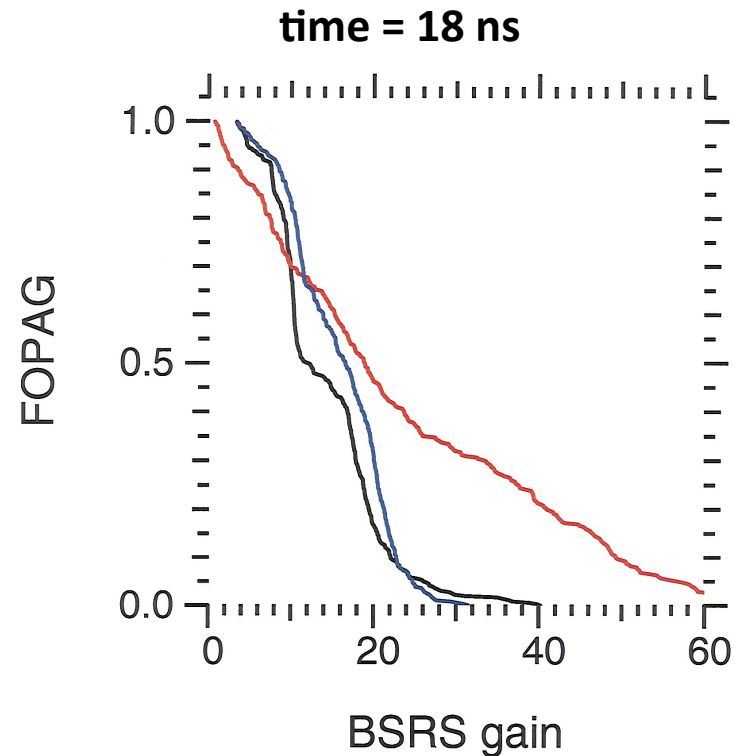
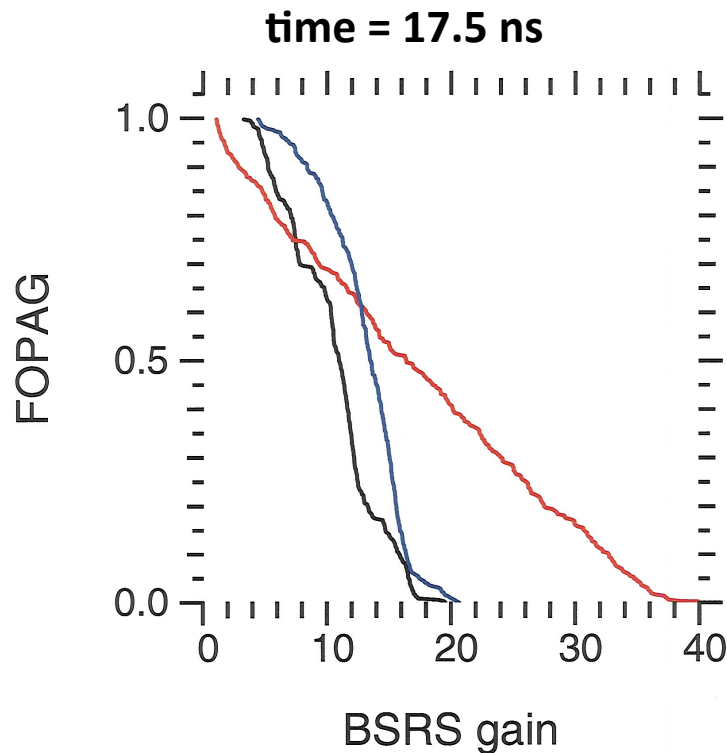
time = 18 ns – mid peak power



- Long-wavelength SRS washed out in ray-averaging, since each ray has a narrow peak (weak damping) at a different wavelength.
- Long-wavelength SRS may not occur: shorter-wavelength SRS occurs at lower density, nearer the LEH, and may deplete the pump.
- If it does occur, it will be more refracted than shorter-wavelength light [c.f. J. Moody's talk] and may miss the FABS detectors.
- Also, it will be more absorbed in the target by inverse bremsstrahlung.

— FABS intensity [a. u.]  
— multi-quad ray-avg. gain  
- - - multi-quad log [ ray-avg. exp (G) ]

# Spatially varying beam transfer gives a wider distribution of ray gains



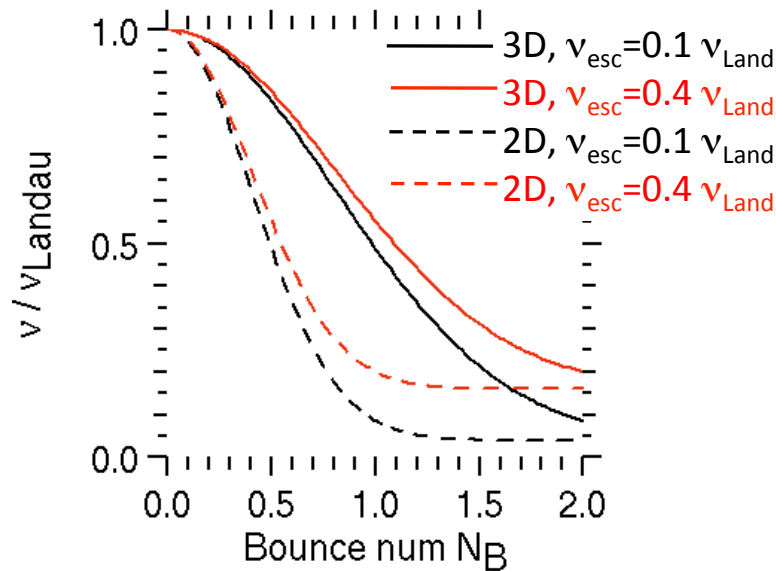
single-quad gain, uniform xfer  
multi-quad gain, uniform xfer  
single-quad gain, varying xfer

FOPAG = fraction of ray power above a gain.

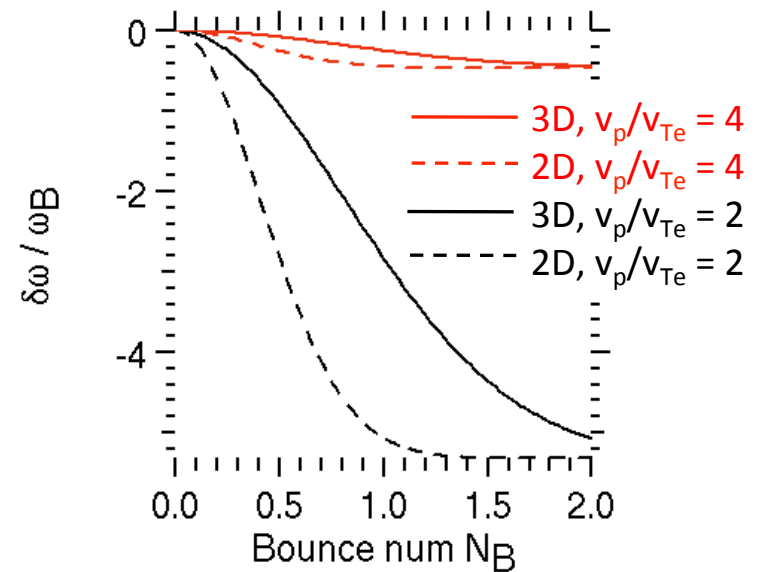
For each ray: find the max gain within  $\lambda = \pm 10$  nm of  $\langle \lambda_{\max} \rangle_{\text{avg}}$ .

# Damping reduction and frequency shift in finite-radius Langmuir wave: theory by H. A. Rose

**Damping Reduction:  
more rapid in 2D than 3D**



**Frequency Downshift:  
rapidly increases with  $k\lambda_D$**



# Fraction of coupling above a bounce number: allows quantification of trapping

$$\frac{dE_{scat}}{dt} \Big|_{coup} \propto E_{las} \delta n_{epw}$$

63.9 ps [black], 65.5 ps [red],  
sideloss + collisions [solid], sideloss [dash]

